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Observation of off-axis directional beaming via subwavelength asymmetric metallic gratings

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The transmission of electromagnetic (EM) waves through a single subwavelength aperture has been studied for many years. As defined in the standard diffraction theory by Bethe [1] in 1944, EM waves that transmit through a subwavelength aperture are fully diffracted in all directions. This disadvantage is the main problem in controlling light. Hence, there have been many studies that have aimed at solving this problem. In 2002, Lezec *et al* [2] showed that it is possible to obtain enhanced as well as directional beaming from subwavelength apertures via the excitation of surface plasmons on corrugated metallic surfaces. Since the reporting of directional beaming through subwavelength apertures, this phenomenon has been intensively researched in its theoretical and experimental aspects [3–7]. Enhanced and directional beaming studies are not just limited to metallic gratings. There is much research activity being conducted on the beaming of light using photonic crystals [8–10]. However, all these studies specifically investigated on-axis beaming.

Changing the beaming angle is another important issue. Therefore, only if we can control both the beaming and the beaming angle can we in turn fully solve the problem of diffraction from a subwavelength aperture. Recently, Kim *et al* [11] proposed a method for changing the beaming angle, and Lin *et al* [12] showed that it is possible to obtain off-axis directional beaming at optical frequencies using asymmetric dielectric gratings. However, to our knowledge, there has not been any scientific work that demonstrates off-axis directional beaming by using metallic gratings in the microwave regime. In this work, we investigated the steering of beaming via a subwavelength metallic aperture with asymmetric surface gratings. By using this new structure, we were able to change the beaming angle and attain off-axis directional beaming.

Surface plasmons are the collective excitation of electrons at the surface of a conductor in the longitudinal direction. Since surface plasmon modes have longer wave vectors than the light waves of the same energy, EM radiation does not interact with the surface plasmon modes of a smooth metal surface. However, when the metal surface surrounding the subwavelength aperture is corrugated, the incident light can couple to surface waves that mimic surface plasmons [2]. The metallic structures that were used in this work have a subwavelength slit ($\lambda/10$) at the centre. The details of the structures are shown in figure 1. The grating period on the input side is 16mm for all three structures. At microwave

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Abstract
It is possible to obtain enhanced and directional beams using subwavelength metallic structures. However, the enhanced beams throughout such structures are only directed towards the propagation direction. In this study, we design the output surface gratings asymmetrically in order to steer the beaming angle. We use a metallic structure with a subwavelength slit ($\lambda/10$) and grating periods of 14mm and 22mm on different sides of the output surface. We demonstrate off-axis directional beaming in the microwave regime with an FWHM of 10° with a beaming angle of 15°. The beaming angle can be changed by arranging the grating periods of the output surface of the metallic structure.

(Some figures in this article are in colour only in the electronic version)

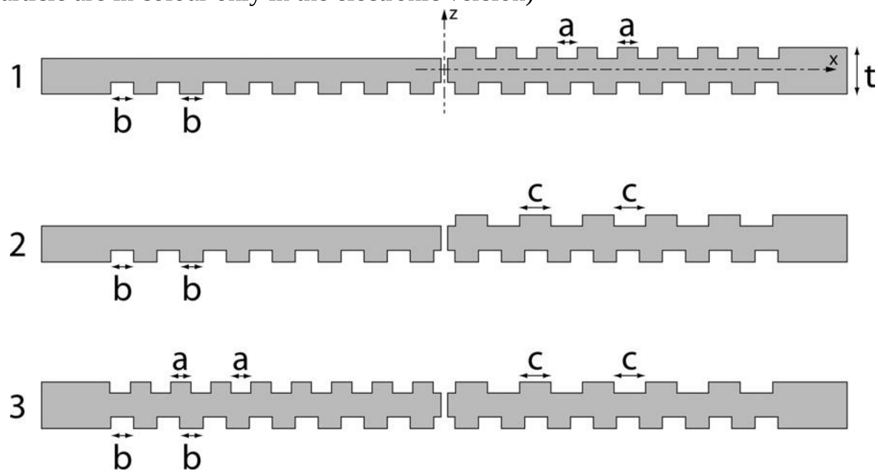


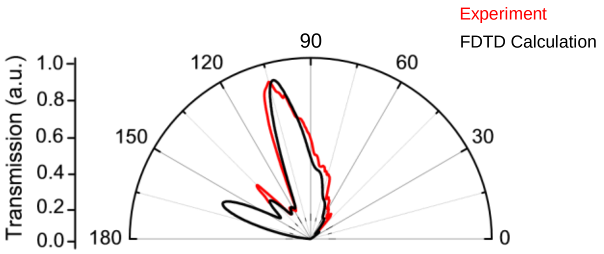
Figure 1. The structures used in this work were a = 7mm, b = 8mm, c = 11mm and t = 16mm. The slit widths were 2mm and the grating heights were 4mm. All of them had the same input surface grating period of 16mm in order to couple the 'spoof' surface plasmons.

frequencies, surface plasmons are too weakly bound to the surface; therefore the, EM response from these structures is governed by the surface modes [13] and they are frequently referred to as 'spoof' surface plasmons or 'designer' surface plasmons. The gratings on the input side of the structures stand for the coupling of surface modes. The grating period of 16mmexecutesaresonanceataround14.5GHz(20.7mm)[4]. On the one hand, the output surface is responsible for the beaming effect [2,14]. When the subwavelength aperture is illuminated on the side of the grooved surface (no grooves on the exit surface), the beam diffracts in all directions. However, a beaming effect occurs when the sample is illuminated so that the output surface is grooved. The emitted EM waves are confined to a narrow spatial region when the output surface of the subwavelength aperture was surrounded by periodic gratingssincethesurface-wavemomentumandthemomentum of the corrugation around the subwavelength aperture limit the allowed range of momentum of the reradiated EM waves.

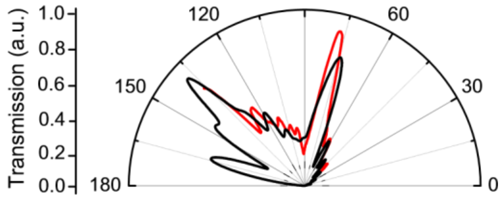
The beam is directed on the axis of the propagation direction, if the subwavelength aperture has symmetric grating periods on different sides of the output surface. However, it is possible to steer the beaming angle by using asymmetric grating periods. In order to optimize the grating periods, we first investigated the structures with gratings only on one side. We calculated the angular distribution of the transmission for a structure with a grating period of 14mm on one side of the output surface (Sample 1). In this study, calculations were performed by using the commercial software (FULLWAVE), which uses the finite difference time domain (FDTD) method. In the simulation, an EM wave with an E field that was polarized in the x direction is incident from the bottom. After thefieldpassesthroughtheaperture,itemitsinthe+zdirection. The EM waves throughout Sample 1 are mostly directed to the negative side (we defined the right side of the 90° as positive and the left side as negative) at 14.5GHz (figure 2(a)).

The measurements were performed in the microwave spectrum at 14.5GHz. The experimental setup consists of a Hewlett Packard 8510C network analyzer and two standardgain horn antennas in order to measure the transmission amplitude. Radiation is normally incident upon the sample from 15cm by the source antenna. We have chosen p-polarization (TM polarization). The receiver antenna was placed 100cm (≈50λ) away from the sample's back face and wasconnectedtoarotatingarminordertomeasuretheangular dependence of the radiation. We observed that most of the EM waves radiated towards the side without grating at around −15° for Sample 1 at 14.5GHz, which corresponds to the spoof plasmon resonance frequency (figure 2). This is also in agreement with the FDTD calculations.

AlthoughtheEMwavesthroughoutSample1weremostly directed towards −15°, the beam was not collimated to the narrow range. In order to obtain off-axis directional beaming we need to arrange the other side of the sample with a period that is different from 14mm. We optimized this period by FDTD calculations to where the structure emits EM waves to the positive side. The calculated transmission for the structure

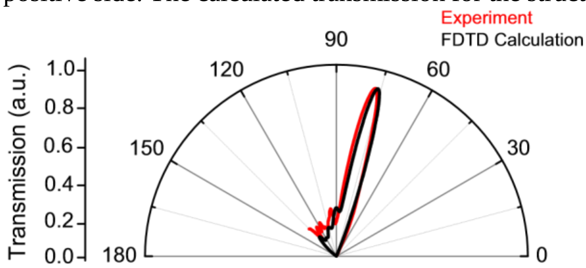


(a)



(b)

Figure 2. The beaming angle is steered for structures with grating periods only on one side of the output surface. The beam is mostly directed to the negative side for (a) Sample 1 and positive side for (b) Sample 2 at 14.5GHz (20.7mm).



Experiment

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FDTD Calculation

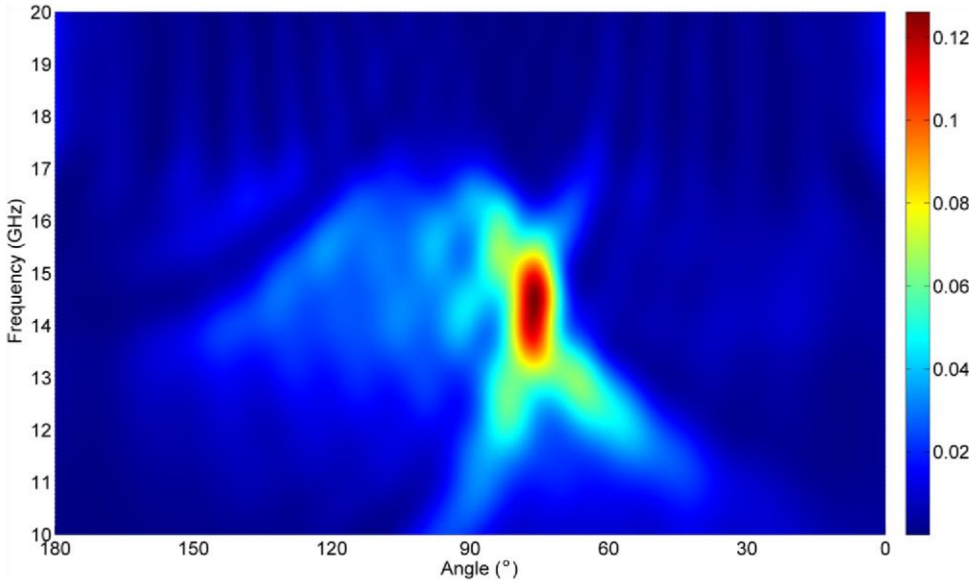


Figure 3. The calculated transmission throughout Sample 3 shows that off-axis and directional beaming is possible by using metallic asymmetric gratings on the output surface at resonance frequency (14.5GHz).

Figure 4. By use of a metallic structure with a subwavelength aperture at the centre and the grating periods of 14mm and 22mm on the different sides of the output surface, we observed off-axis directional beaming with an FWHM of 10° and the beaming angle of 15°. It is possible to steer the beaming angle by arranging the grating periods of the output surface of the metallic structure.

with a grating period of 22mm (Sample 2) shows that most of the emitted EM waves were directed towards the positive side. In the measurements of our second sample, we observed a beam at 15° on the positive side (figure 2(b)). This case is the exact opposite of Sample 1.

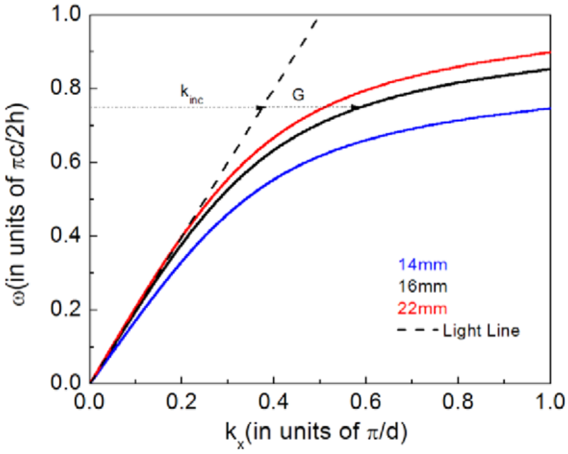
It is possible to steer the beam by only using Sample 1 or 2. However, the beaming is not as clear for them. In order to obtain off-axis as well as directional beaming, we combined these two structures (Sample 3). The combination of these gratings will provide a directional yet off-axis beam through the positive side. The calculated transmission between 10 and 20GHz from Sample 3 shows that at the resonance frequency (14.5GHz) the emitted EM waves were directed towards the positive side (figure 3). Meanwhile, we measured the angular distribution of the EM waves that were transmitted through Sample 3 with asymmetric grating periods on different sides. We observed off-axis directional beaming with a beaming angle of 15° and a full-width half-maximum (FWHM) of 10° (figure 4). 12% of the power is transmitted from the metallic structure with a subwavelength aperture at the resonance frequency. This result is in good agreement with the FDTD calculations. Since the beaming angle only depends on the grating periods of the output side, this angle can be changed easily by arranging the output grating periods asymmetrically. We have also presented the FDTD mode pattern showing the coupling between the top and bottom surfaces at the resonance frequency (figure 5).

This phenomenon can be explained by the use of the dispersion relation of the surface bound states. The dispersion relation of the surface modes is given as [13]

$$\frac{\sqrt{k_x^2 - k_0^2}}{k_0^2} = \frac{a}{d}\tan(k_0 h),$$

where h is the depth of the grooves, a is the groove width and d isthegrooveperiod. Infigure6weplotthedispersionrelations for groove periods 14mm and 22mm. This dispersion relation is related to the beaming angle of the off-axis directional beaming appearing. The angle between the wavevector of the surface mode and the incident EM wave gives the beaming angle. The calculated beaming angles using this dispersion relation are 14° and 16° for metallic structures with groove periods of 14mm and 22mm, respectively. These results are in agreement with FDTD calculations. It is also possible to describe the angular width and the propagation direction with grating coupler formulae.

In conclusion, we were able to change the beaming angle of the directional beaming by using metallic asymmetric gratings on the output surface. By using a metallic structure with a subwavelength aperture at the centre and the grating periods of 14mm and 22mm on the different sides of the output surface, we observed off-axis directional beaming with an FWHM of 10°. We showed that the beaming angle is 15°. Furthermore, these results are in good agreement with the FDTD calculations. Our results show that it is possible to steer the beaming angle by arranging the grating periods of the output surface of the metallic structure.



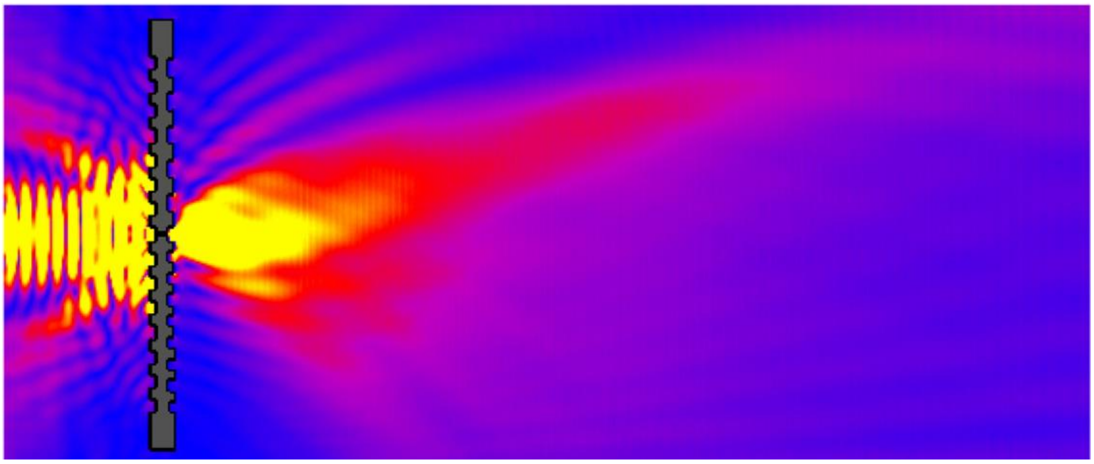


Figure 5. FDTD mode pattern showing the coupling between the top and bottom surfaces at the resonance frequency.

Figure 6. The dispersion relation of the surface modes supported by metallic structures with grooves of periods 14mm (blue line), 16mm (black line) and 22mm (red line). The light line is shown with a dashed line. (Colour online.)

Acknowledgments

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References

[1] Bethe H A 1944 Theory of diffraction by small holes *Phys. Rev.* **66** 163182

[2] Lezec H J, Degiron A, Devaux E, Linke R A, Martin-Moreno L, Garcia-Vidal F J and Ebbesen T W 2002 Beaming light from a subwavelength aperture *Science* **297** 820–2

[3] Yu L B, Lin D Z, Chen Y C, Chang Y C, Huang K T, Liaw J W, Yeh J T, Liu J M, Yeh C S and Lee C K 2005 Physical origin of directional beaming emitted from a subwavelength slit *Phys. Rev.* B **71** 041405

[4] Caglayan H, Bulu I and Ozbay E 2005 Extraordinary grating-coupled microwave transmission through a subwavelength annular aperture *Opt. Express* **13** 1666–71

[5] Poujet Y, Roussey M, Salvi J, Baida F I, Labeke D, Perentes A, Santschi C and Hoffmann P 2006 Super-transmission of light through subwavelength annular aperture arrays in metallic films: spectral analysis and near-field optical images in the visible range *Photon. Nanostruct.* **4** 47

[6] Garcia-Vidal F J, Martin-Moreno L, Lezec H J and Ebbesen T W 2003 Focusing light with a single subwavelength aperture flanked by surface corrugations *Appl. Phys. Lett.* **83** 4500

[7] Mart´ın-Moreno L, Garc´ıa-Vidal F J, Lezec H J, Degiron A and Ebbesen T W 2003 Theory of highly directional emission from a single subwavelength aperture surrounded by surface corrugations *Phys. Rev. Lett.* **90** 167401

[8] Moreno E, Garcia-Vidal F J and Martin-Moreno L 2004 Enhanced transmission and beaming of light via photonic crystal surface modes *Phys. Rev.* B **69** 121402

[9] Bulu I, Caglayan H and Ozbay E 2005 Beaming of light and enhanced transmission via surface modes of photonic crystals *Opt. Lett.* **30** 3078

[10] Kramper P, Agio M, Soukoulis C M, Birner A, Muller F,¨ Wehrspohn R B, Gosele U and Sandoghdar V 2004 Highly¨ directional emission from photonic crystal waveguides of subwavelength width *Phys. Rev. Lett.* **92** 113903

[11] Kim S, Kim H, Lim Y and Lee B 2007 Off-axis directional beaming of optical field diffracted by a single subwavelength metal slit with asymmetric dielectric surface gratings *Appl. Phys. Lett.* **90** 051113

[12] Lin D Z, Cheng T D, Chang C K, Yeh J T, Liu J M, Yeh C S and Lee C K 2007 Directional light beaming control by a subwavelength asymmetric surface structure *Opt. Express* **15** 2585–91

[13] Garcia-Vidal F J, Martin-Moreno L and Pendry J B 2005 Surface with holes in them: new plasmonic metamaterials *J. Opt. A: Pure Appl. Opt.* **7** S97–S101

[14] Caglayan H, Bulu I and Ozbay E 2006 Plasmonic structures with extraordinary transmission and highly directional beaming properties *IEEE Microw. Opt. Technol. Lett.* **48** 2491